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Correction Techniques for Depth Errors With Stereo Three-Dimensional Graphic Displays

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Correction Techniques for Depth Errors With Stereo Three-Dimensional Graphic Displays

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Summary

Three-dimensional (3-D), "real-world" pictorial displays that incorporate "true" depth cues via stereopsis techniques have proved effective for displaying complex information in a natural way to enhance situational awareness and improve pilot/vehicle performance. In such displays, the display designer must map the depths in the real world to the depths available with the stereo display system. However, the human subject does not perceive the information at exactly the depth at which it is mathematically placed. Head movements can also seriously distort the depth information embedded in stereo 3-D displays because the transformations used in mapping the visual scene to the depth-viewing volume (DVV) depend intrinsically on the viewer location. The goal of this research has been to provide corrections for depth errors to the lateral disparity calculations used to generate stereo displays. Two correction techniques are presented; the first technique corrects the original visual scene to the DVV mapping based on human perception errors, and the second corrects for errors induced by head movements based on head-positioning sensor input data.

Empirical data have been gathered which compare perceived depth via subject judgment (from physical probe placements) against computed depth (from lateral disparity calculations). The data are presented to validate both correction techniques. The first technique of recomputing the depth placement of objects so that they are perceived at the desired depth is a simple linear relation, and data are presented which compare perceived depth error with and without the correction technique. The head-movement correction technique involves transformations based on the six degrees of freedom for head movement. Of these six degrees of freedom, the most critical in terms of effects on lateral disparity calculations is the forward and backward head movement. The other five degrees of freedom, for various reasons, have negligible effects on lateral disparity. Validation data for the forward and backward head movement are presented for the cases of no head movement, head movement without correction, and head movement with correction.

A combination of both correction techniques effectively eliminates the distortions of depth information embedded in stereo 3-D displays. The head-movement distortions of depth information are most disruptive with large-screen displays (e.g., projected displays) which allow some freedom for head movement. These errors are less disruptive for small, head-down displays because head movement is somewhat constrained by circumstance. The same correction techniques can be applied to stereo displays in helmet-mounted displays, which have inherent unrestricted head movement.

Introduction

The 3-D, real-world pictorial displays are provided by displaying to each eye a disparate view of the visual scene using various display hardware systems; in these displays, the right eye sees only the right-eye scene and the left eye sees only the left-eye scene. Lateral disparity, which is the horizontal displacement of an object from the center of the screen to a stereo-pair presentation, is used to place the object at some depth from the screen.

The 3-D presentation of 3-D information, rather than the conventional two-dimensional (2-D) display of such information, has become an accepted practice in fields such as meteorology, molecular modeling, medical imaging, and computer-aided design (CAD). The application of stereo technology also has been investigated for years within the flight display community. These efforts have been particularly intense for helmet-mounted head-up display applications because the display of stereopsis cueing information has been readily available with binocular helmet systems (refs. 1 to 4). Additional investigations that utilize electronic shutters or polarized filters rather than helmet optics to present separate left- and right-eye views have also been conducted (refs. 4 to 12).

Subjective and objective results from most of these studies indicated that the depth cues provided by the stereo displays enhanced the situational awareness of the pilot and improved pilot/vehicle performances. Stereopsis cueing was not only effective in situational awareness enhancements of pictorial displays but also offered the potential to declutter complex informational displays and to provide more effective alerting functions to the flight crew.

A knowledge of where and how accurately a subject perceives the depth cues placed within the DVV (the volume around the viewing screen in which objects may be perceived by an observer as being either in front of, at screen depth, or behind the screen) is essential to enable effective displays for precision control tasks. Placement of the objects within the DVV, based on the mapping of the visual scene to the DVV, is not sufficient because the human subject does not perceive the object at exactly the depth at which it is mathematically placed (ref. 9). Head movements can also seriously distort the depth information embedded in stereo 3-D displays because the transformations used in mapping the visual scene to the DVV depend intrinsically on the viewer location.

The goal of this research has been to provide corrections for depth errors to the lateral disparity calculations used to generate stereo displays. Two correction techniques are presented; one technique corrects the original visual scene to the DVV mapping based on human perception errors, and the second corrects for errors induced by head movements based on head-positioning sensor input data.

After presenting background information concerning stereo display generation, the problems of depth perception errors and head-movement distortions are discussed. A description of the equipment involved in the generation of stereo displays and the correction calculations follows. The correction technique for depth perception errors with no head movement is then discussed. This technique allows the display designer to place depth information at perceived depth locations rather than at the computed depth locations (where they would be perceived incorrectly). Data are presented, both with and without the correction technique, which compare perceived depth error via subject judgment (from physical probe placements) against computed depth (from lateral disparity calculations).

The head-movement correction technique then is addressed. This technique involves transformations based on the six degrees of freedom for head movement. Of these six degrees of freedom, the most critical in terms of effects on lateral disparity calculations is the forward and backward head movement. The other five degrees of freedom, for various reasons that are discussed, have negligible effects on lateral disparity. The forward and backward movement changes the screen distance for both eyes, and this movement has a large effect on lateral disparity. The lack of correction for this movement is quite noticeable. A detailed explanation of the forward and backward movement effects on the observer for stereo displays will therefore be presented.

Because of the significance of the forward and backward movement in stereo displays, validation data comparing perceived depth error against computed depth are presented for the cases of no head movement, forward and backward head movement without correction, and head movements with correction.

Symbols and Definitions

Symbols

a	elevation angle of line connecting points in r, rad
b	$= \sin^{-1}(i/2r)$, rad
D	screen distance, in.
D_c	corrected screen distance, in.
d	depth, in.
d_c	corrected depth for screen distance D for object placed at d, in.
i	interocular separation distance, in.
r	distance between center of rotation of head and midpoint of observer's eyes, in.
x	forward and backward translation of head from calibration position (initial zero condition), in.
y	lateral disparity, in.
Θ	pitch rotation of head from calibration position (initial zero condition), rad
Ψ	yaw rotation of head calibration position (initial zero conditions), rad

Definitions:

accommodation	change in focus accomplished by change in lens thickness of eye, which changes focal length
binocular	viewed by both eyes
binoptic	both eyes being presented with same image
depth-viewing volume	volume provided by stereopsis display techniques, encompassing space both in front of and behind CRT screen; in this paper, determination of this volume concerns only depth component, excluding consideration of height and width components
diplopia	double vision, a condition induced by use of large lateral disparities
interocular distance	lateral distance between two retinas of eye, in.
lateral disparity	horizontal displacement of object from center of screen to stereo-pair presentation required to place object at some depth from screen

lateral retinal disparity	positional differences occurring in two different views of visual scene from viewpoints separated by lateral distance that scales interocular distance between two retinas of eye
monoscopic	viewed by one eye only
stereopsis cueing	display of information utilizing depth dimension and introduced by means of lateral disparity
vergence	rotational movement of eye to align each eye with point in scene; in real-world viewing, muscles rotate eyes outward or inward so that lines of sight of both eyes intersect at depth distance of object being fixated

Stereopsis Techniques

High-fidelity, 3-D displays that incorporate true depth in the display elements are provided by displaying to each eye a disparate view of the visual scene. Various display hardware systems present the two views to the observer such that the right eye sees only the right-eye scene and the left eye sees only the left-eye scene. These hardware systems include refracting or reflecting stereoscopes and systems that incorporate electronic or mechanical shutters or polarized or color filters. Helmet-mounted systems depend on a direct presentation of each eye view.

Regardless of the display hardware system, graphics software is necessary to create the left- and right-eye stereo-pair images. The graphics generation computer performs this task by resolving the single-viewpoint visual data base stored within it into the desired stereo pair (as described in the section entitled "Graphics Generation Hardware and Software." Figure 1 illustrates the parallax concept that is employed to produce objects behind the monitor screen via stereo pairs. Figure 2 illustrates the concept as it is employed to produce objects at various depths. The heavy horizontal line represents the screen of the display monitor. To present an object that appears at the depth of the screen, the object is drawn in the same location for both stereo-pair views. For objects to appear behind the screen, the object is displaced from that position to the left for the left-eye view and to the right for the right-eye view (with the displacement reaching a maximum value to place an object at infinity). For objects to appear in front of the screen, a displacement to the right is used for the left-eye view and to the left for the right-eye view.

Depth Cues

In binoptic or monoscopic displays of perspective real-world scenes, a great deal of depth information is provided by such cues as linear perspective, relative size, shape, object interposition, motion perspective, motion parallax, texture gradients, and shading. Stereoscopic displays of such scenes add the cues of lateral retinal disparity (the positional differences occurring within the retinas of the eyes in two different views of the visual scene from viewpoints separated by a lateral distance that scales the interocular distance between the two retinas) and the muscular movement and tension cues associated with vergence (the rotational movement of the eyes to align each eye with a point in the scene). In real-world viewing, the muscles rotate the eyes outward or inward so that the lines of sight of both eyes intersect at the depth distance of the object being fixated.

In stereoscopic displays, the introduction of lateral disparity initiates vergence to create a perceived depth (fig. 1). Although lateral disparity and vergence are usually interdependent and nonseparative, the physiological cues associated with the eye muscles controlling vergence movements are separate cues from those of lateral disparity in the psychophysical and physiological literature (refs. 13 and 14). Stereoscopic displays thus produce both the muscular cues and the disparity/vergence cues associated with depth perceptions.

Other depth cues that are present in real-world viewing are changes in focus (accommodation) and pupil size (although pupil size remains constant for object distances greater than approximately 3 ft). In stereoscopic displays, the viewing distance that affects both accommodation and pupil size is the screen distance (the eye to image source distance), which remains constant. Thus, the major depth cue missing in the synthetic generation of stereoscopic displays is the change in accommodation with fixation-point depth, and it is, indeed, a major lack because accommodation and convergence are highly interactive. For a fixed accommodation distance, a limited range of vergence conditions exist which will result in comfortable, clear, fused, single vision. This restriction implies that for a given screen distance for a stereoscopic display, limits exist to the amount of lateral disparity that is usable by the display designer. These limits require the display designer, in the case of real world pictorial displays, to map the depths in the real world to the depths available with the stereo display system. Figure 3 illustrates the mapping of a real-world scene to the stereo-viewing volume.

Depth and Lateral Disparity Relationship

Figure 4 presents the geometric relationship between lateral disparity and depth for objects appearing behind the screen, which is the case of positive disparity (divergent, or uncrossed, disparity). By similar triangles,

$$y = \frac{id}{2(D + d)}$$

Objects appearing in front of the screen (negative d) obey the same equation, and they have negative disparity (negative y, for convergent, or crossed, disparity). The maximum positive disparity considered allowable under any circumstances is one-half the interocular distance, which would produce parallel lines of sight (for objects at infinity). The maximum negative disparity would be limited for objects along the centerline to one-half the width of the screen. However, these extremes will far exceed the limits for comfortable, usable viewing (ref. 9).

Depth Perception Problem

In reference 9, a determination is made of the usable DVV that is available for the practical use of stereo displays. This effort involves the presentation of an object to an observer at a computed depth via the stereoscopic display technique by using a one-to-one mapping of the real world to the stereo-viewing volume. The observer then positions a physical probe (a real-world probe) to the distance that represents where the image is perceived to be. Figure 5 (taken from ref. 9) presents the 95-percent confidence intervals for perceived depth from the display screen; these intervals are a function of the computed depth from the screen from the lateral disparity values for a screen distance of 19 in. The data represent the results of 192 trials in which four subjects judged four repetitions at each depth position. A straight line with a slope of 1 is also presented in the figures, thus representing the ideal case of perceived depth coinciding with computed depth. For objects placed in front of the screen, the occurrence of severe object blurring limits the usable volume. Increasing the object depth (lateral disparity) in front of the screen results eventually in diplopia (double vision). For objects placed behind the screen, the depth perceived is increasingly larger than that presented; that is, the farther the object is placed behind the screen, the larger the error becomes. This fact is true, at least, until the extremes of the computed depths examined in the experiment are reached. The size of the confidence intervals about the perceived depth means within these extreme regions is such that these regions are not usable for practical applications.

Figure 6 (also taken from ref. 9) presents the 95-percent confidence interval for perceived depth error as a function of computed depth, with both normalized to the screen distance of 19 in. The positive error represents objects that are perceived as too far from the observer, and the positive depth placement represents objects placed behind the viewing screen. Subjects are much more accurate in their perceived depth estimates for the in-front images compared with the behind-the-screen conditions. However, as objects are placed farther in front of the screen and closer to the observer, they quickly begin to blur. Even though the distance judgments are more accurate, the usable volume in front of the screen is smaller than the usable volume behind the screen. Reference 9 suggests an arbitrary criteria of comfortable, unblurred single vision in front of the screen and, equally arbitrarily, less than 10-percent perceived depth error behind the screen to determine the usable DVV. These criteria result in a usable DVV that falls between -0.25 and 0.6 of the screen distance (the 10-percent error criteria are marked with lines in fig. 6). Within this practical DVV, subjects will consistently overestimate the depth of objects placed behind the screen of the display system but with less than a 10-percent error. The in-front depth estimates will be essentially correct.

Head-Movement Problem

Stereo displays are created by generating left- and right-eye views of the display; these displays are presented such that the right eye sees only the right-eye scene and the left eye sees only the left-eye scene. The introduction of lateral disparity into the stereopair initiates vergence to create a perceived depth. The top portion of figure 7 again illustrates the parallax concept that is used to produce objects behind the monitor screen via stereo pairs. If the subject viewing a stereo display moves away from the display screen and the lateral disparity remains constant (i.e., it is not corrected for this movement), the perceived object will appear to retreat farther from the screen (as illustrated in the bottom portion of fig. 7). Conversely, if the subject moves forward toward the screen, the object appears to also move toward the screen. Thus, any foward or backward head movement effect is exaggerated by the accompanying object movement. To further confuse the viewer, objects presented in front of the screen perversely move in directions opposite to those of objects located behind the screen (fig. 8). Therefore, the forward and backward head movement can seriously distort the depth information embedded in stereo 3-D displays.

The other five degrees of freedom, for the various reasons now discussed, have negligible effects on lateral disparity. However, some movements in those degrees of freedom can have dramatic effects on the visual scene. The standard matrix transformation equations are used to account for those effects (ref. 15). Because the transformation matrix equations are not modified to affect lateral disparity for stereo displays, they are not presented.

Movements in the vertical plane by a seated observer, by nodding the head (vertical rotation, or pitch) or stretching or slumping the neck and body (vertical translation), are necessarily small. Because these movements are orthogonal to the lateral disparity axis, they have a negligible effect on the lateral disparity calculations. Pitch movement does change the screen distance slightly, and vertical movement is a simple translation of the viewpoint of both eyes. Both effects are easily accommodated within the matrix transformation equations and within the stereo head-movement correction equation (which is presented in the section entitled "Head-Movement Correction").

Lateral plane movements by a seated observer, which are made by turning the head (lateral rotation, or yaw) or shifting the body to the left or right (lateral translation), also have negligible effects on lateral disparity. Yaw movement does change the screen distance slightly for both eyes, but the main visual effect is to rotate the vanishing point of the scene in a horizontal direction about the point of disparity application. The vanishing point is the point of perspective convergence, that is, the point to which parallel lines, viewed in perspective, converge. The change in vanishing point is a dramatic visual change, but it does not affect lateral disparity calculations.

Likewise, lateral movement (which is a simple translation of the viewpoint of both eyes) is another dramatic visual change that has no effect on the lateral disparity. In fact, correcting for lateral movement (and/or vertical movement) provides stereo displays with a "look-around" capability, or a holographic-like capability, which is quite impressive. Again, both lateral plane effects are easily accommodated within the transformation equations and the stereo head-movement correction equation.

Seated observer movements in the other two degrees of freedom, by rolling the head or shifting the body in the forward or backward direction, can have large effects on lateral disparity. Roll-movement correction requires transferring lateral disparity to vertical disparity such that the depth position of objects in the scene does not change. However, head roll angles in practical applications are usually small so that the correction, or lack of it, is barely noticeable. Provisions within the transformation equations and the stereo head-movement correction equation to account for roll movements are included, however.

Experimental Apparatus

The experiment was conducted utilizing a graphics display generator and associated stereo software, a display format, the stereo display system hardware, a six degree-of-freedom magnetic head position sensor, and an observer station (fig. 9).

Graphics Generation Hardware and Software

The graphics generation hardware consisted of a Silicon Graphics IRIS 70 GT. Graphics software within the graphics generator was used to generate the stereo pairs with the required lateral disparity. First, left- and right-eye coordinate systems were created as offsets from the viewer coordinate system of the visual scene. (See ref. 15 for a discussion of computer graphics principles.) Clipping then was employed to limit each eye view to the display surface boundaries. Finally, simple perspective division was used to transform the 3-D viewing volumes to 2-D view ports whose centers were offset from the center of the display screen by one-half of the maximum-allowed lateral disparity (which was used to represent objects at infinite distance).

Visual Display Format

The display format utilized in the depth determination task consisted of three elements: a horizon line that separated blue sky from brown earth, as typically used in electronic attitude display indicators; a single vertical rod that was always located at screen depth for reference purposes and was in the middle of the display monitor; and a duplicate vertical rod that was located at the calculated depth from the screen by means of lateral disparity in the stereoscopic display. The latter rod, which was used as the depth target, was positioned such that the left-most image of the stereo pair never was positioned off the screen, and the virtual image produced by the stereo pair always was located 2.5 in. from the left side of the Cathode-ray tube (CRT) monitor. The horizon line was banked to the left by 3° so that it could conceptually represent infinity. (With zero bank, the horizon line could not exhibit any lateral disparity and, hence, no depth.) This horizon line was presented with a lateral disparity of $i/2$ for each subject. The two vertical rods were identical in size, regardless of the relative depths, such that no perspective cues were available. Figure 10 illustrates the full-screen display format (as would be observed by a subject).

Stereo Display System Hardware

The stereo display system hardware operated by modifying the video signals supplied by the graphics display generation system. These video signals presented a noninterlaced frame at 60 Hz and consisted of both the left- and right-eye stereo-pair images. (Fig. 11 presents the display as drawn by the graphics generation system in a stereo-pair arrangement.) The stereo display system hardware separated the left- and right-eye scenes and presented each alternately (at 120 Hz) spread across the entire monitor screen (i.e., time-multiplexed stereo, which resulted in a 50-percent loss in vertical resolution), as shown in figure 10. A screen-mounted liquid-crystal shutter was synchronized with the stereo pair such that with polarized glasses, the right eye saw only the right-eye scene and the left eye saw only the left-eye scene, each at 60 Hz, without flicker. The stereo visual system hardware was developed by the StereoGraphics Corporation (ref. 16).

Head Position Sensor

The head position sensor used (ref. 17) consisted of a receiver module, which was attached to the stereo goggles, and a transmitter module, which was fixed in a rigid position approximately 6 in. above the subject's head for the 19-in. screen distance setup. The system which was specified to provide the six-degree-of-freedom movements about the calibration zero point within a cubic volume of 20 in. per side, had a precision of less than 0.5 in. translationally and 0.5° rotationally at an update rate of 60 Hz.

Observer Station and Task

The observer station consisted of a chair, a headrest (to ensure that the observer remained at the required screen distance), and a physical probe for matching the perceived depth of an image with the actual depth of a probe (fig. 12). The probe was pencil shaped and mounted vertically at the end of a push stick. For images perceived as being behind the screen, the observer's task was to position the movable probe (by using a horizontal movement of the push stick) to an actual depth behind the screen which the observer believed matched the perceived depth of the image presented on the CRT screen. The movable probe was constrained to move along the left side of the CRT without the observer's view (with both eyes) of the probe being obstructed by the monitor. The observer, therefore, was not forced to move his head to view either the image or the probe, thus ensuring a maintenance of accurate screen distance.

To locate images that were perceived as being in front of the CRT screen, the observer held the push stick horizontally in front of the screen to position the pencil-shaped probe that was mounted vertically at the end of the stick. Placement of the probe was therefore intrusive to the stereoscopic display, whereas the behind-the-screen probe did not impinge upon the display. Both probes required the observer to adjust his accommodation cues from the screen distance to the probe distance. These changes in accommodation between screen and probe were expected to result in more accurate distance judgments for both the real and the virtual objects.

Experimental Procedure

Three subjects were presented with randomized computed depths, with three replicates of each depth position occurring during the data collection sessions. Six sets of data were gathered. Two sets dealt with the depth-perception correction technique, which consisted of one set each for the uncorrected perception case with no head movement and another set for the perception-corrected case with no head movement. The other four sets dealt with head movement, and all four sets utilized the depth-perception correction technique. These sets consisted of the perception-corrected case with a 20-percent forward head movement, both with and without head-movement corrections, and of the perception-corrected case with a 20-percent backward head movement, both with and without head-movement corrections. The cases with head movement were not dynamic; i.e., the head position remained fixed after the original displacement. The initial position of the depth probe was randomized before the presentation of the next depth condition to avoid any possible hysteresis effects.

Results and Discussion

Both the correction for depth-perception errors and for head movement are discussed.

Depth-Perception Correction

The first technique of recomputing the depth placement of objects so that they are perceived at the desired depth is a simple linear relation. This relation has been extracted from the data presented in figure 5 within the practical DVV of reference 9. The volume is defined as an in-front depth limit of 25 percent of the screen distance and a behind-the-screen depth limit of 60 percent of the screen distance. Let d_c be the corrected depth for screen distance D for an object placed at depth d. Then

$$d_c = 0.884d - 0.016D \qquad (d > -0.14D)$$

$$d_c = d \qquad (d \leq -0.14D)$$

Figure 13 presents the empirical data (with the means averaged over all subjects and replicates) gathered and compares the perceived depth via the subject judgment (from physical probe placements) against the computed depth (from lateral disparity calculations) to validate the depth-perception correction technique. The positive error represents objects that are perceived as too far from the observer, and the positive depth placement represents objects placed behind the viewing screen. The technique of recomputing the depth placement of objects so that they are perceived at the desired depth has been quite successful, as evident from the comparison of perceived depth error with and without the correction technique.

This technique has been so successful, in fact, that one might consider using it to extend the usable DVV for behind-the-screen objects. Reference 9 suggests a 10-percent confidence interval error criterion for the behind-the-screen limit (at 0.6 times the screen distance depth), and the correction technique certainly reduces the mean error at the 0.6 depth placement point. However, as seen in figure 6, near that extreme (the 0.6 depth placement point), the confidence interval about the mean is rapidly deteriorating because of large increases in the standard deviations. Also, the slope of the mean curve begins to change rapidly and becomes less than 1, and the errors become smaller. As the image is placed farther behind the screen, the positive slope of the perceived depth error curve (which is ideally zero) eventually becomes negative. This phenomenon is not investigated further in reference 9 because the region is beyond the recommended practical limits of usable depth. Reference 9 suggests, however, that this region might represent the limits of perceivable depth; that is, no matter how much farther an image is placed behind the screen, it is still perceived by the observer to be the same distance away, at least until diplopia occurs.

Head-Movement Correction

The head-movement correction technique involves transformations based on the six degrees of freedom (three rotational and three translational) for head movement, which are supplied to the graphics generator by the magnetic head position sensor (fig. 9). In addition, the standard matrix transformation equations (ref. 15) are used to correct the viewpoint locations of both eyes for head movement. Because the matrix equations are not modified for stereo displays, they are not presented.

The effect of head movement on the stereo calculations involves only the changes in screen distance which must be accounted for within the mapping transformations (from the real-world scene to the stereo DVV, as shown in fig. 3).

For the derivation, let r equal the distance between the center of the head's rotation and the midpoint of the observer's eyes, a equal the elevation angle of the line connecting those two points, i equal the interocular separation distance, D equal the screen distance, x equal the forward and backward translation of the head from the calibration position (initial zero condition), and Θ and Ψ equal the pitch and yaw rotations, respectively, of the head from the calibration position (at initial zero condition). Also, let b equal the $\sin^{-1}(i/2r)$ and D_c equal the corrected screen distance. Then

$$D_c = D + x + 2r\cos a \sin^2\frac{\Theta}{2} + r\sin a \sin\Theta$$
$$+ 2r\cos b \sin^2\frac{\Psi}{2} + r\sin b \sin\Psi$$

Experimental Results

Figures 14 and 15 present the empirical data from three subjects (nine trials per data point) which validate the head-movement correction algorithm. The percent of perceived error is plotted against the object depth placement position (both axes are normalized to screen distance) for both a 20-percent backward head movement (fig. 14) and a 20-percent forward head movement (fig. 15). Curves are presented for the cases of no head movement, head movement without correction, and head movement with correction. A positive error represents objects that are perceived as too far from the observer, and a positive depth placement represents objects placed behind the viewing screen.

The head-movement correction technique effectively eliminates the distortions of depth information embedded in stereo 3-D displays caused by head movement. These errors are most disruptive with large-screen displays (e.g., projected displays), which allow some freedom for head movement. The errors are less disruptive for small, head-down displays because head movement is somewhat constrained by circumstance (e.g., the viewer of a small-screen display tends to remain near the center of the display, while the viewer using a large-screen display feels less restricted in movement).

Concluding Remarks

The goal of this research was to provide corrections for depth errors to the lateral disparity calculations used to generate stereo displays. Two correction techniques were presented; one technique corrected the original visual scene to the depth-viewing volume (DVV) mapping based on known human perception errors, and the second corrected for errors induced by head movements based on head-positioning sensor input data.

Empirical data were gathered which compared perceived depth via subject judgment (from physical probe placements) against computed depth (from lateral disparity calculations). The data were presented to validate both correction techniques. The technique of recomputing the depth placement of objects so that they were perceived at the desired depth was successful; this success was evident from the comparison of perceived depth error with and without the correction technique. Because the technique was so successful, it might be considered for use to extend the usable DVV for behind-the-screen objects; however, the confidence interval about the mean rapidly deteriorates near the limit of the viewing volume because of large increases in the standard deviations. Therefore, accurate perception would, in actuality, not be provided by such an extention.

The head-movement correction technique involved transformations based on the six degrees of freedom for head movement, and the data were presented for the cases of no head movement, forward and backward head movement without correction, and head movement with correction. The head-movement correction technique effectively eliminated the distortions caused by head movement.

A combination of both correction techniques effectively eliminates the distortions of depth information embedded in stereo three-dimensional (3-D) displays. The head-movement distortions of depth information are most disruptive with large-screen displays (e.g., projected displays) which allow some freedom for head movement. These errors are less disruptive for small, head-down displays because head movement is somewhat constrained by circumstance.

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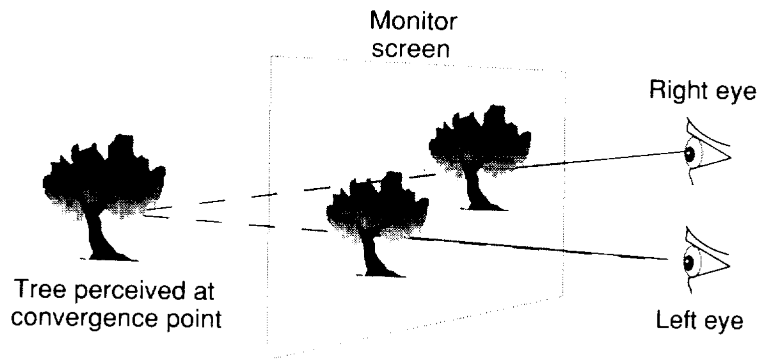

Figure 1. Parallax concept for introducing depth via stereo-pair display.

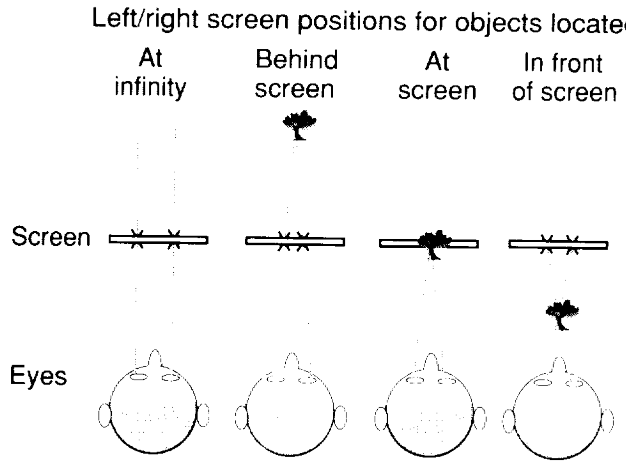

Figure 2. Top view of geometric principle for producing left- and right-eye views.

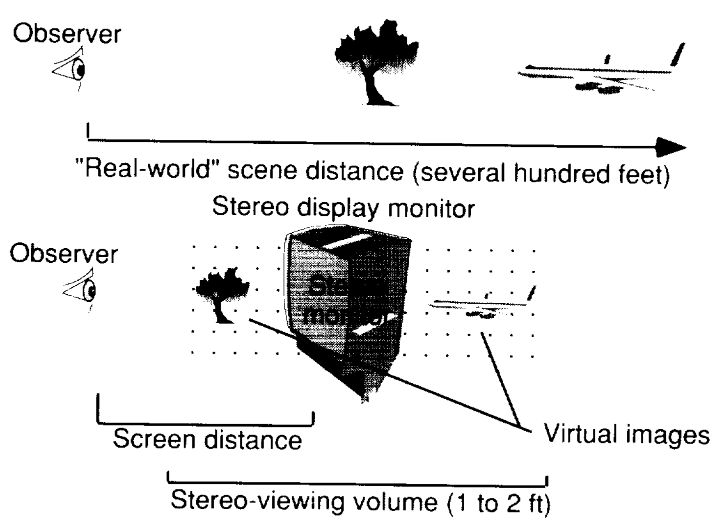

Figure 3. Mapping of "real-world" scene to stereo-viewing volume.

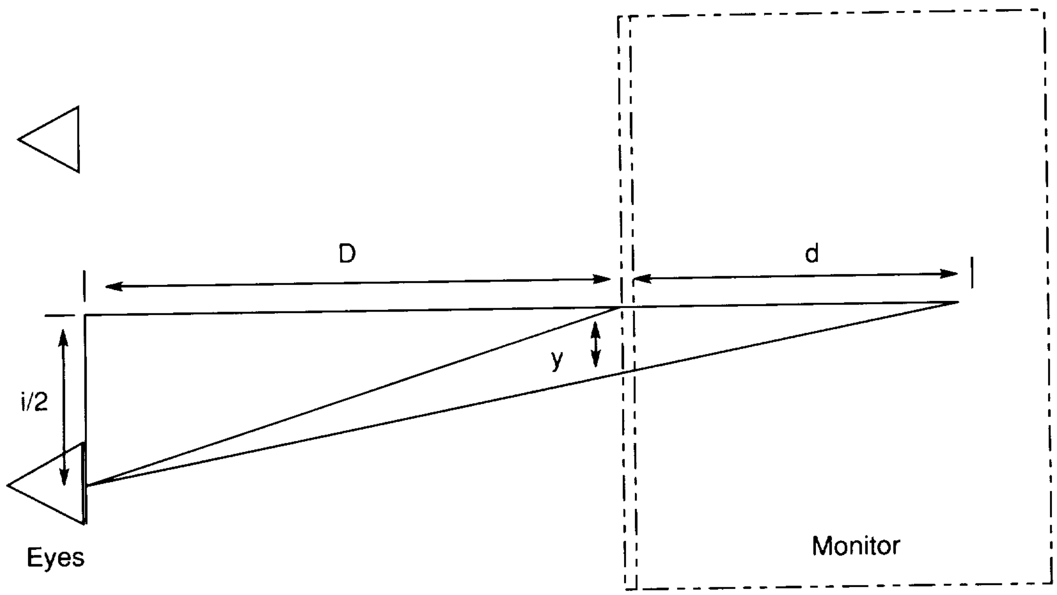

Figure 4. Overhead view of subject and monitor showing relationship between lateral disparity and depth.

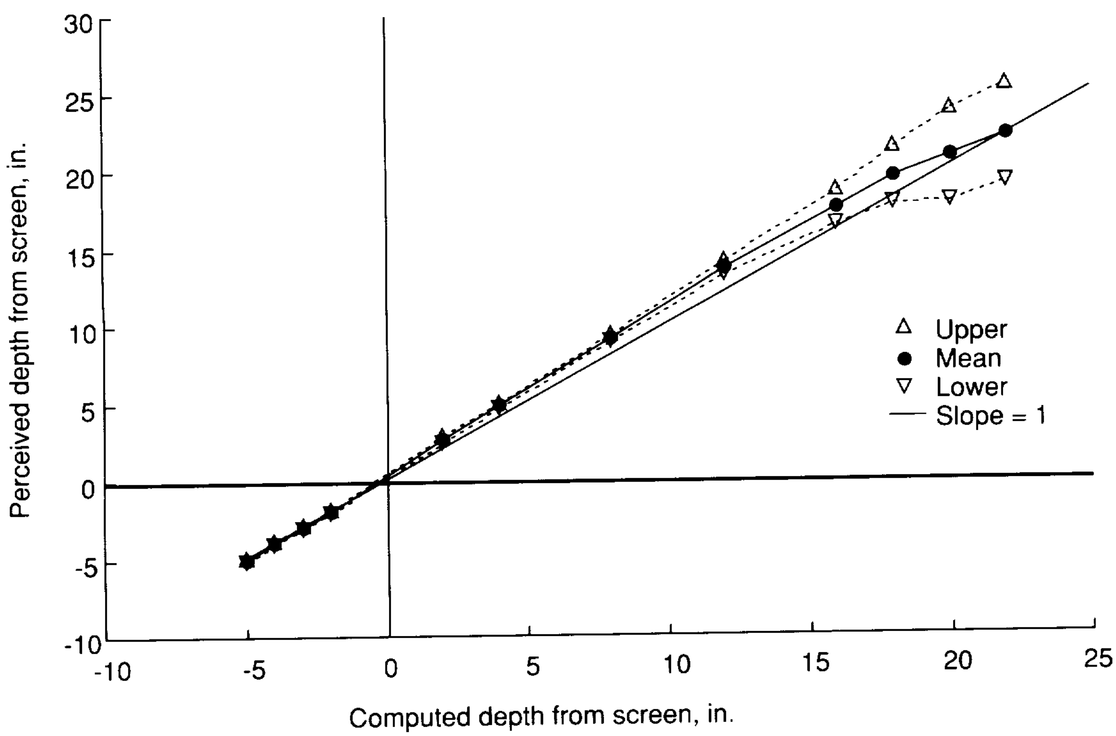

Figure 5. A 95-percent confidence interval for perceived depth as function of computed depth for screen distance of 19 in. (16 trials per point).

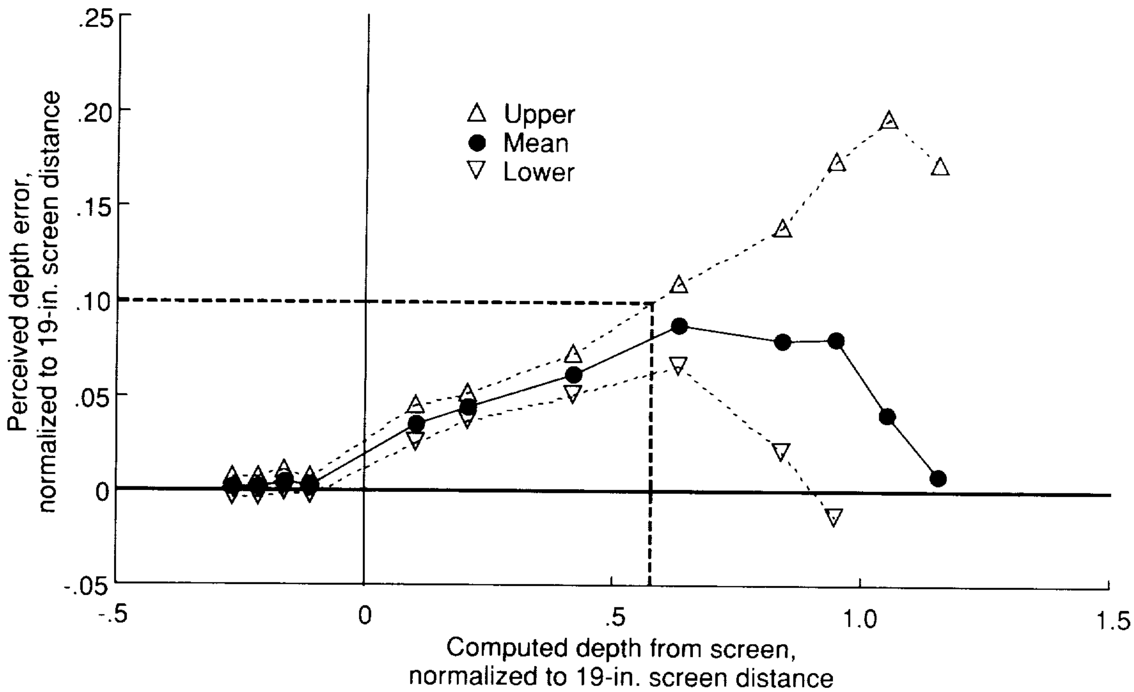

Figure 6. A 95-percent confidence interval for perceived depth error as function of computed depth for screen distance of 19 in. (16 trials per point).

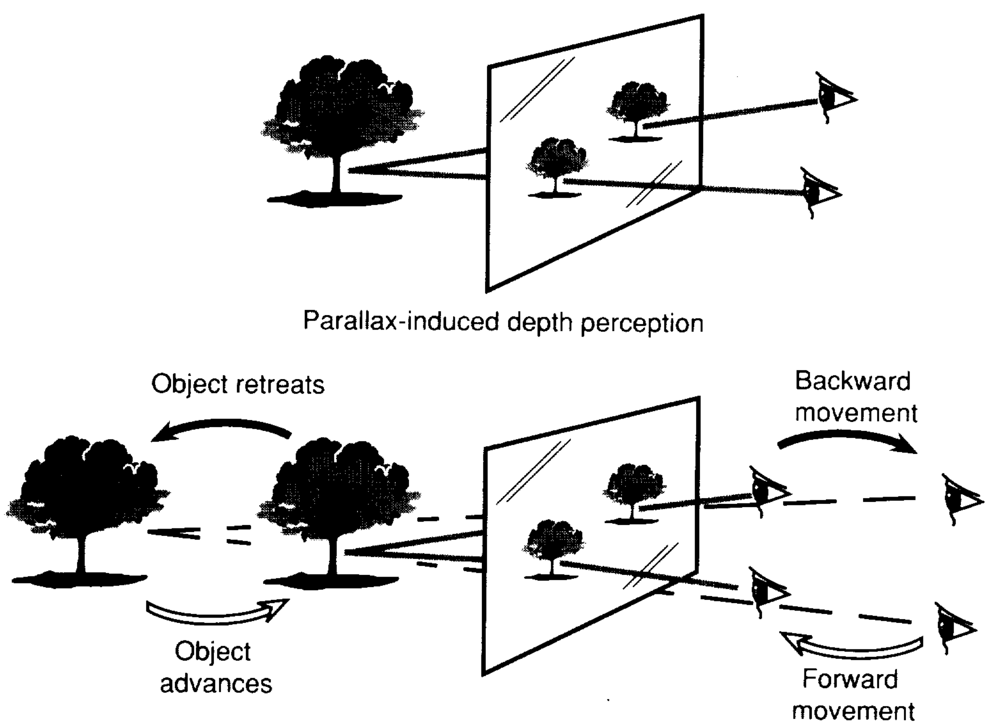

Figure 7. Head-movement effects with constant lateral disparity in stereo 3-D displays.

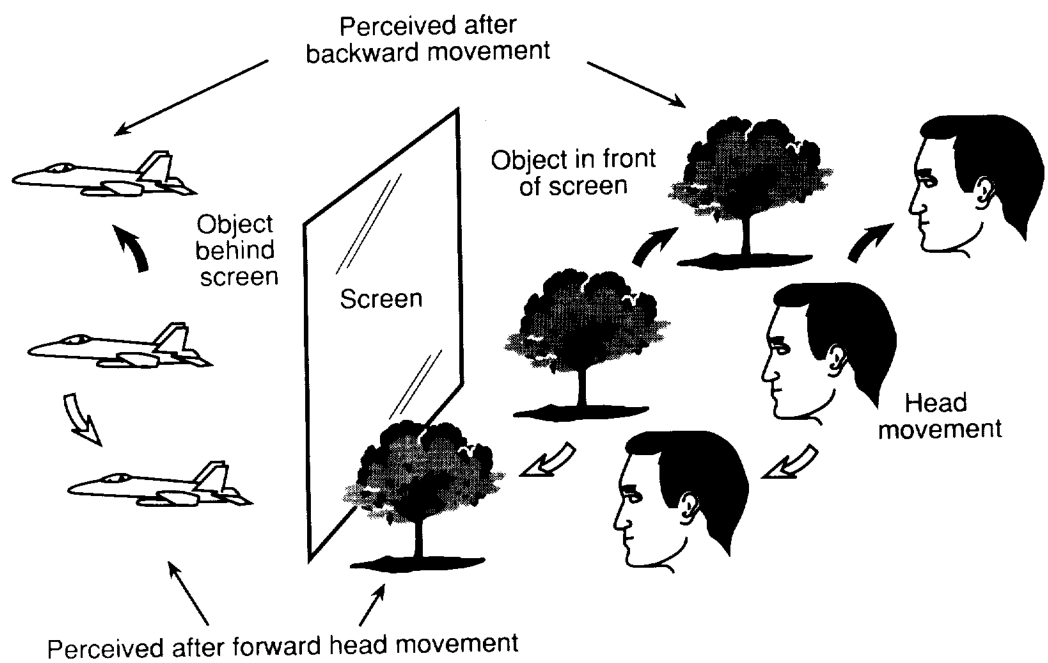

Figure 8. Object translations with head movement.

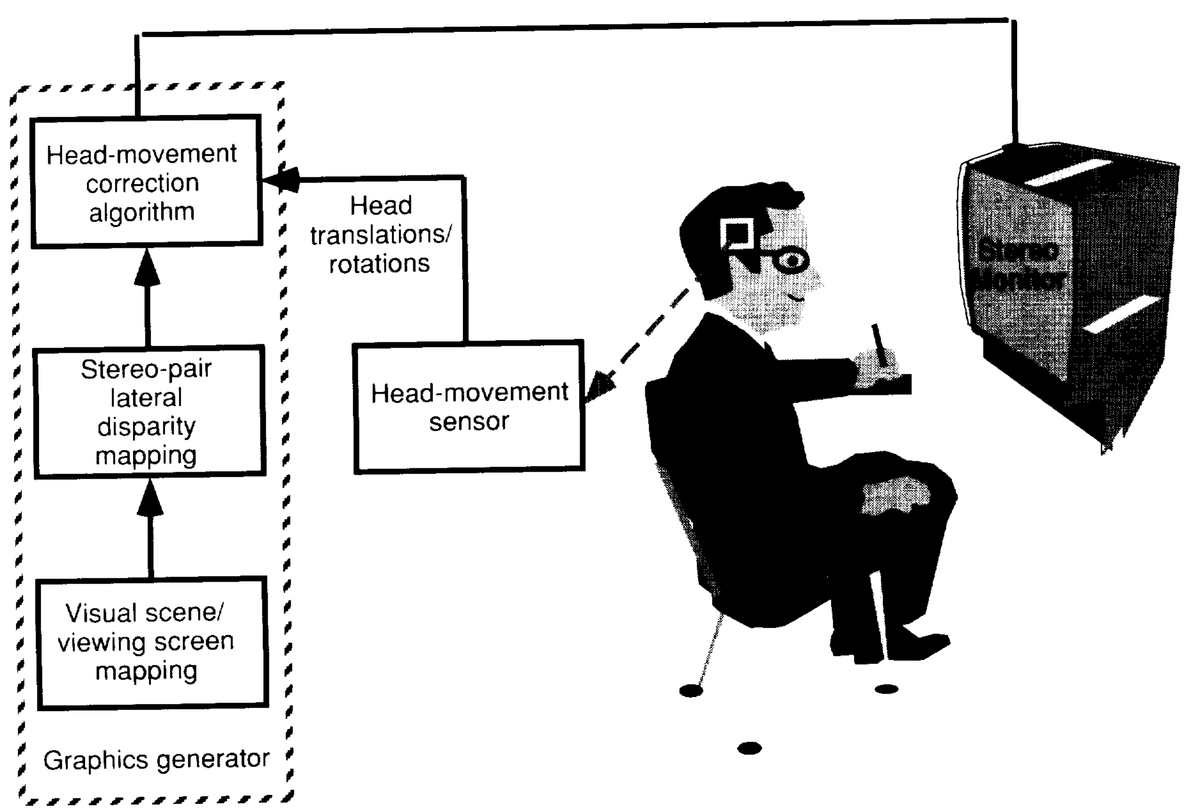

Figure 9. Technique for head-movement correction in stereo 3-D flight displays.

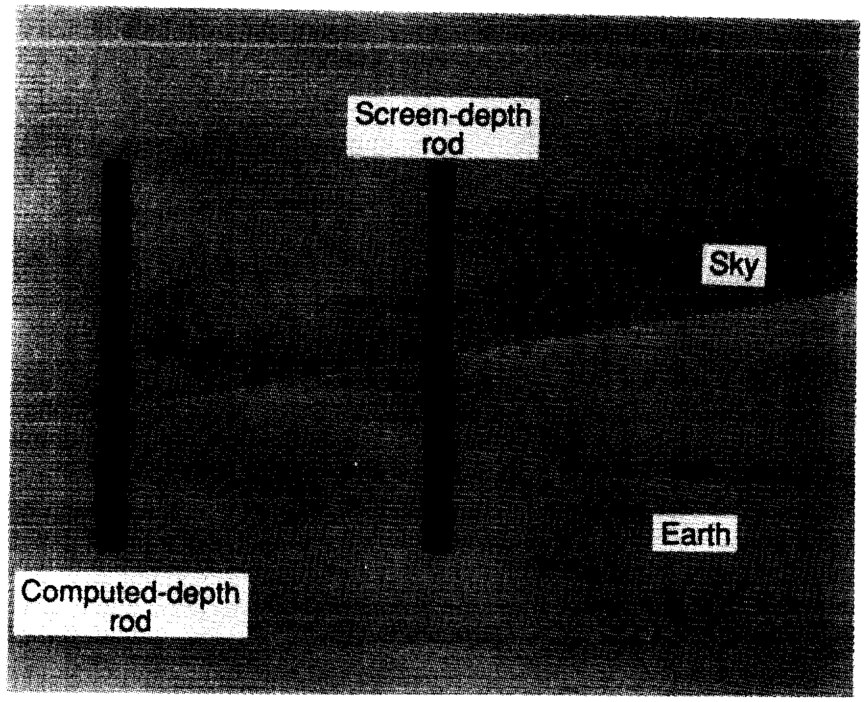

Figure 10. Full-screen nonstereo view.

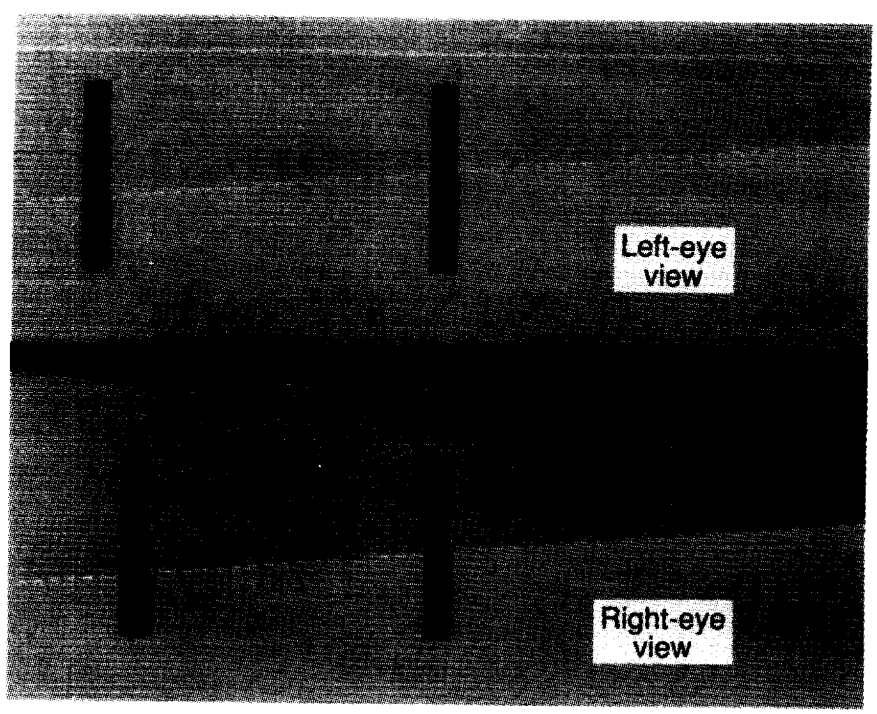

Figure 11. Stereo-pair view of display format.

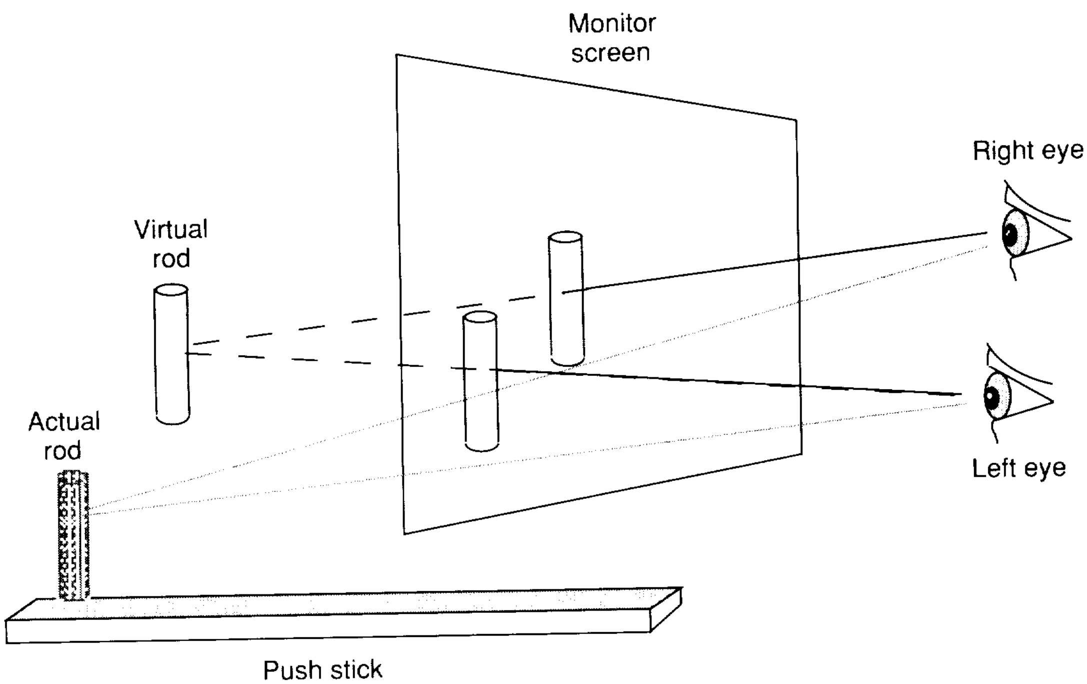

Figure 12. Conceptual view of observer station.

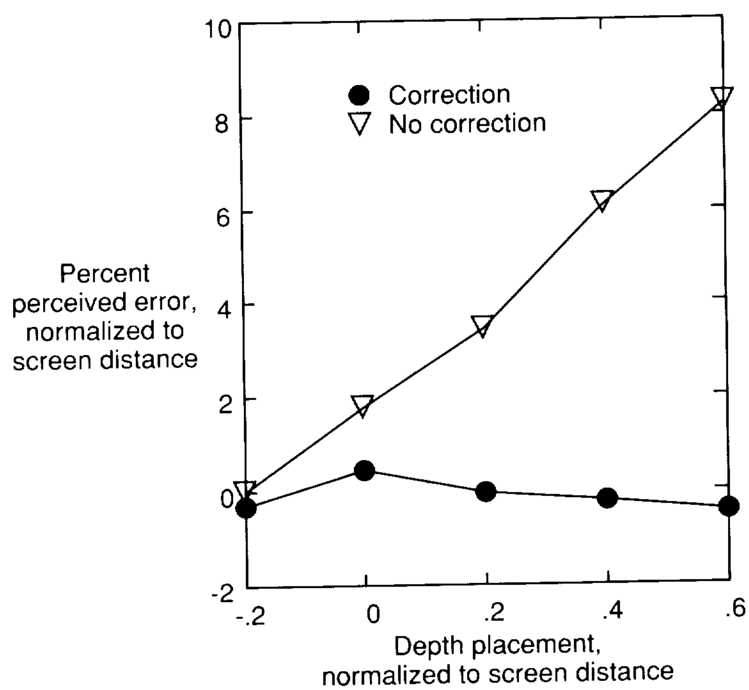

Figure 13. Correction for perceived depth error.

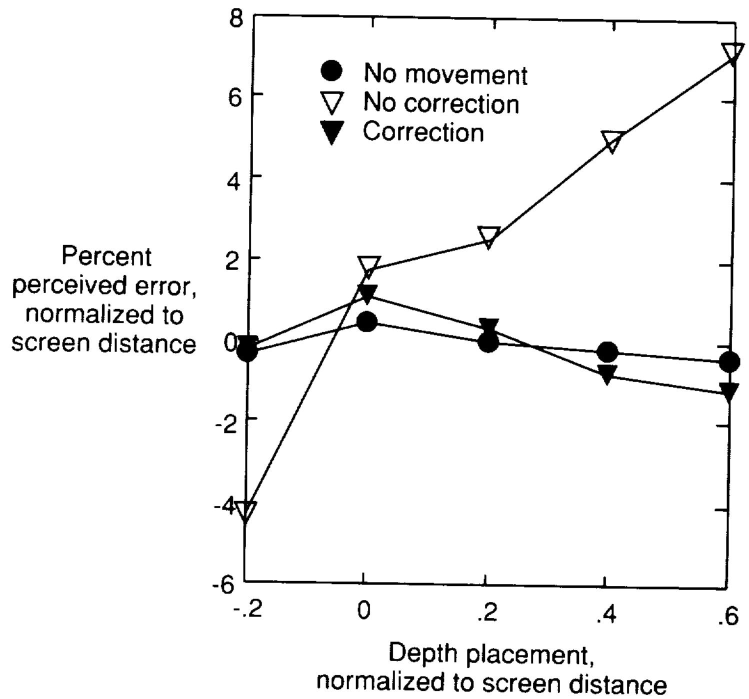

Figure 14. Parallax effect for backward head movement with and without correction.

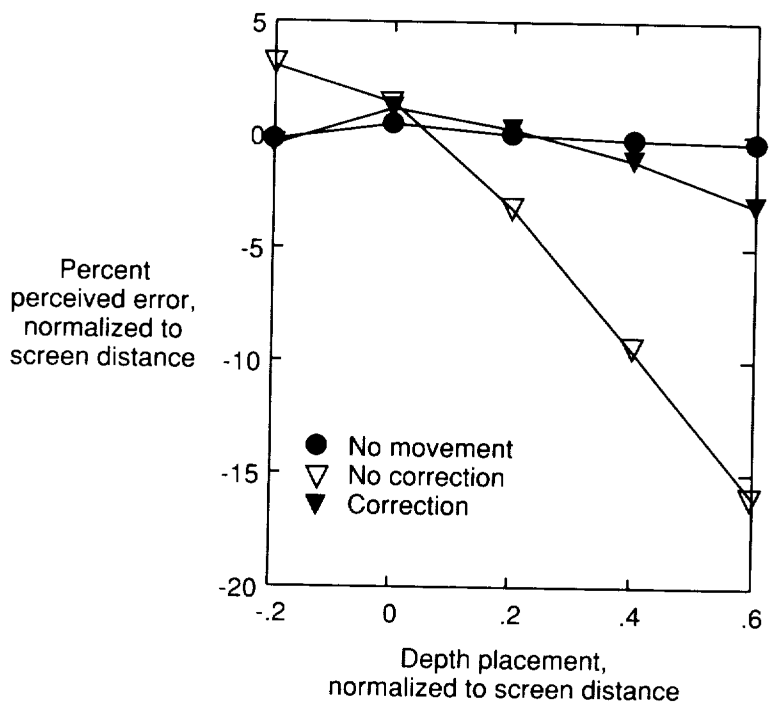

Figure 15. Parallax effect for forward head movement with and without correction.

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13. ABSTRACT *(Maximum 200 words)*
Three-dimensional (3-D), "real-world" pictorial displays that incorporate "true" depth cues via stereopsis techniques have proved effective for displaying complex information in a natural way to enhance situational awareness and to improve pilot/vehicle performance. In such displays, the display designer must map the depths in the real world to the depths available with the stereo display system. However, empirical data have shown that the human subject does not perceive the information at exactly the depth at which it is mathematically placed. Head movements can also seriously distort the depth information that is embedded in stereo 3-D displays because the transformations used in mapping the visual scene to the depth-viewing volume (DVV) depend intrinsically on the viewer location. The goal of this research has been to provide two correction techniques; the first technique corrects the original visual scene to the DDV mapping based on human perception errors, and the second (which is based on head-positioning sensor input data) corrects for errors induced by head movements. Empirical data are presented to validate both correction techniques. A combination of the two correction techniques effectively eliminates the distortions of depth information embedded in stereo 3-D displays.

14. SUBJECT TERMS
Stereo displays; Stereopsis cueing; Head movement; Depth cues

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